

# REPORT DOCUMENTATION PAGE

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1 item enclosed

# ATK Thiokol Propulsion

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**RTO Specialist Meeting on Advances in Rocket  
Propellant Performance, Life and Disposal for Improved  
System Performance and Reduced Costs**

**Aalborg, Denmark**

**“A Solid Rocket Motor Manufacturer’s View of  
Sensors and Aging Surveillance ”**

*Presented by*

**R. Scott Hyde**



000ppt  
23-26 September, 2002



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## History

- There are two basic approaches used to monitor the health of solid rocket motors (SRM)
  - Demonstrated reliability through functional testing
    - Poor-mans approach
    - Higher risk
  - Predictive health management through combined experimental testing and analysis (several variations)
    - More expensive
    - Lower risk

## History Continued

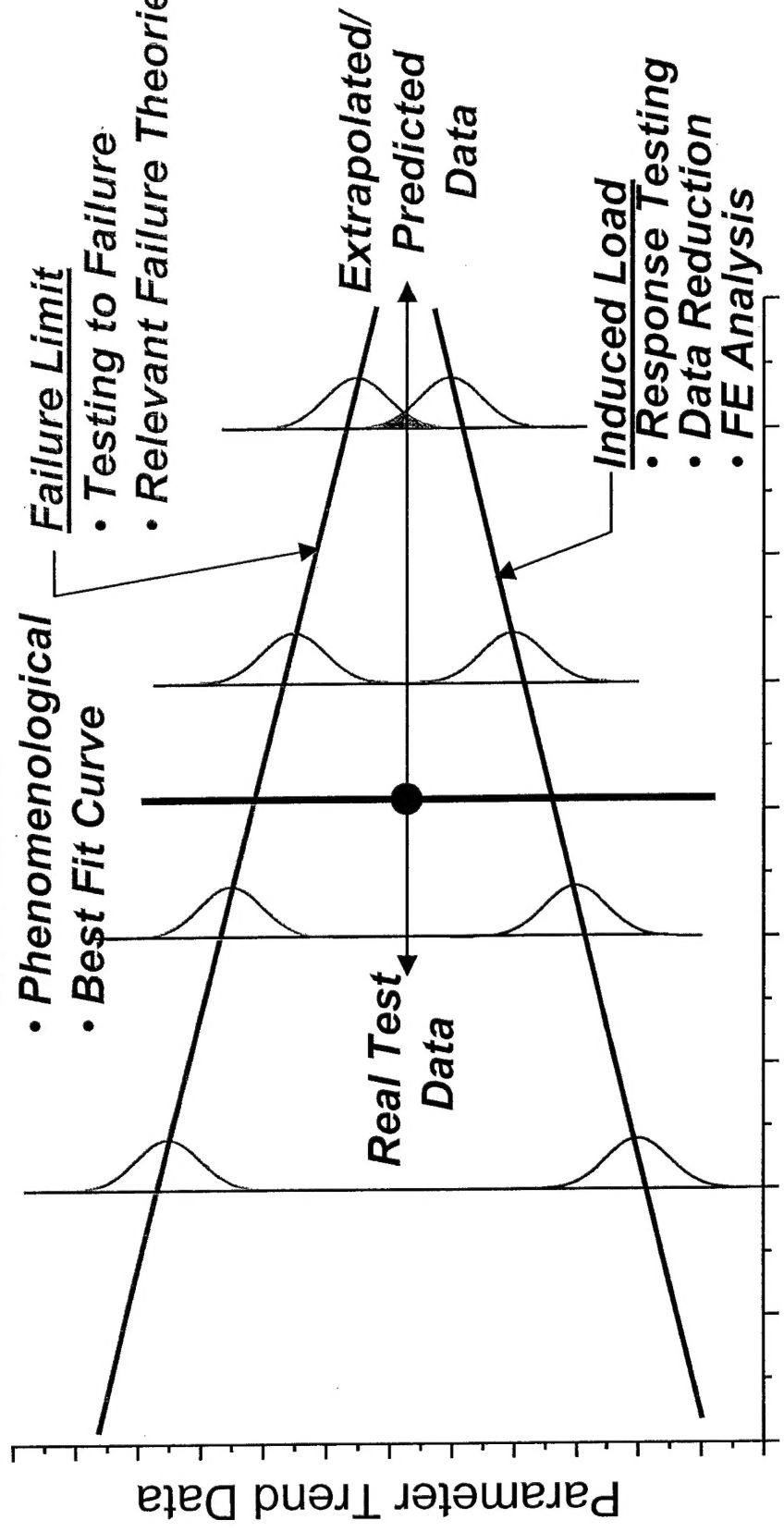
- Predictive/quantitative health monitoring of solid rocket motors (SRM) currently relies on data only obtained through destructive test methods
  - Loads (temperature, pressure, vibration/ acceleration, etc.)
  - Mechanical response and failure properties ( $E$ ,  $\alpha$ ,  $\sigma_f$ ,  $\epsilon_f$ )
  - Chemical properties (stabilizers, curatives, plasticizers oxidative cross-linking, etc.)
- Many attempts have been made to obtain this data more efficiently (cheaper)

# History Continued

## Predictive Health Management Approach

### Extrapolation Methods

- Mechanistic
- Phenomenological
- Best Fit Curve
- Failure Limit
  - Testing to Failure
  - Relevant Failure Theories



Age

## History Continued

- Lessons we have all learned:
  - Dissection, plugging and testing are costly
  - Turning data into information is difficult
  - Limited data used to represent entire force
- Cost has forced some programs to rely on functional testing to demonstrate reliability
  - Feels good but is not effective
  - Chances are highest of finding problem during live operational use

## History Continued

- Many successful past and current uses of sensors for health monitoring
- Large motor program performed full-scale testing of instrumented motors for pressure and thermal loads
  - Sensors measured normal and shear stress, strain, displacement, pressure and temperature
  - Performed testing of instrumented subscale motors under a variety of conditions
- UK is monitoring baseline normal stress of operational motors

## History Continued

- Past and current technology programs have addressed sensor use
  - Extended Service Life Prediction Program
    - Included ultrasonics, infrared sensors, dielectric sensors and fiber optic sensors
  - Propellant/Case Interface Technology Program
    - Included a subtask to relate chemical and mechanical properties at the baseline
  - Service Life Prediction Technology Program
    - Focused on determining the link between chemical and mechanical properties



## Sensor Development

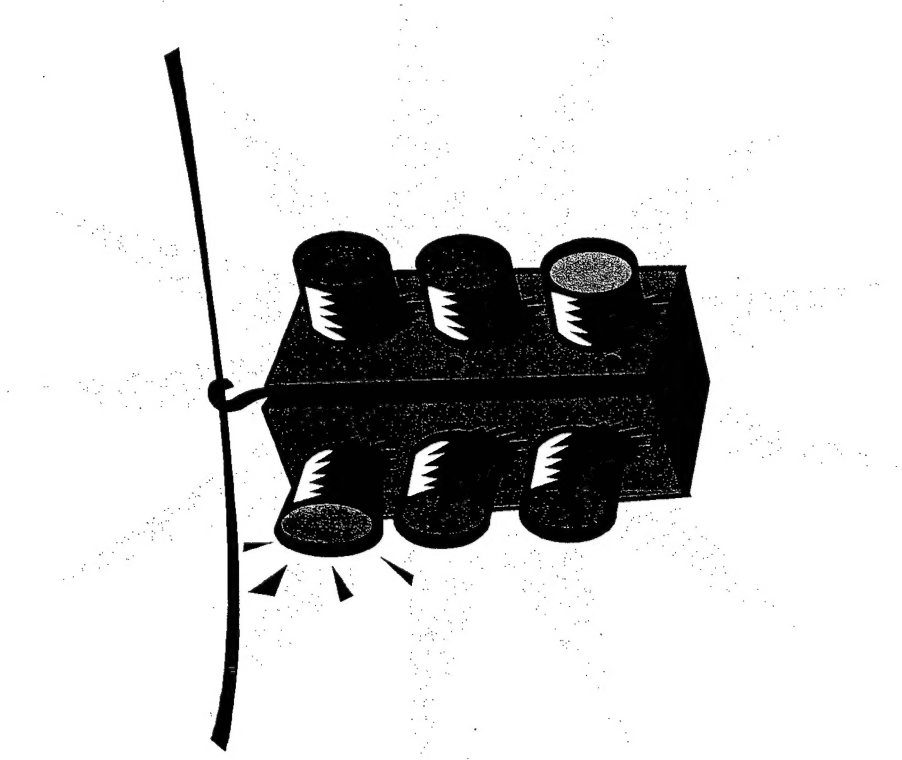
- A common vision and goals for sensors in SRM's does not currently exist but needs to be developed
- SRM industry needs to team with sensor developers
  - Define unique SRM requirements/environments
  - Borrow from work accomplished by other industries
  - Transition COTS technology to SRM requirements

## Sensor Development Continued

Where We Are Headed:

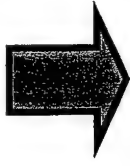
How We Get There:

- Create model to guide sensor development effort
- Define health monitoring for each system
- Integrate design, manufacturing and operational considerations (cradle to grave)



## Sensor Development Model

Identification of  
Desired Measurements



Identification of  
Enabling Technologies



Application of  
Technology



Validation of Applied  
Technology

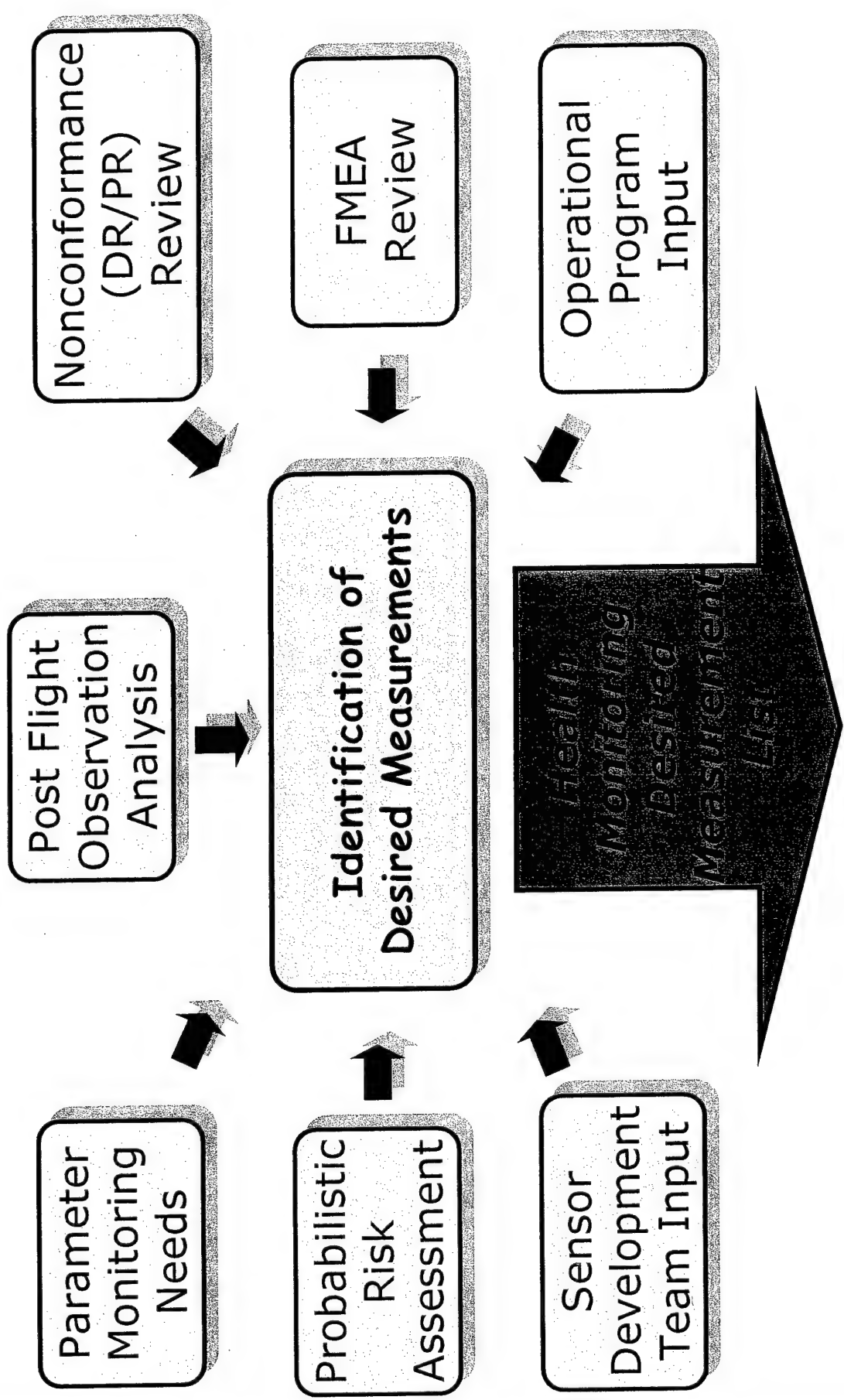
What specific measurements are needed?  
In what specific environments?

What technologies currently exist  
to obtain such measurements?  
COTS or development required?

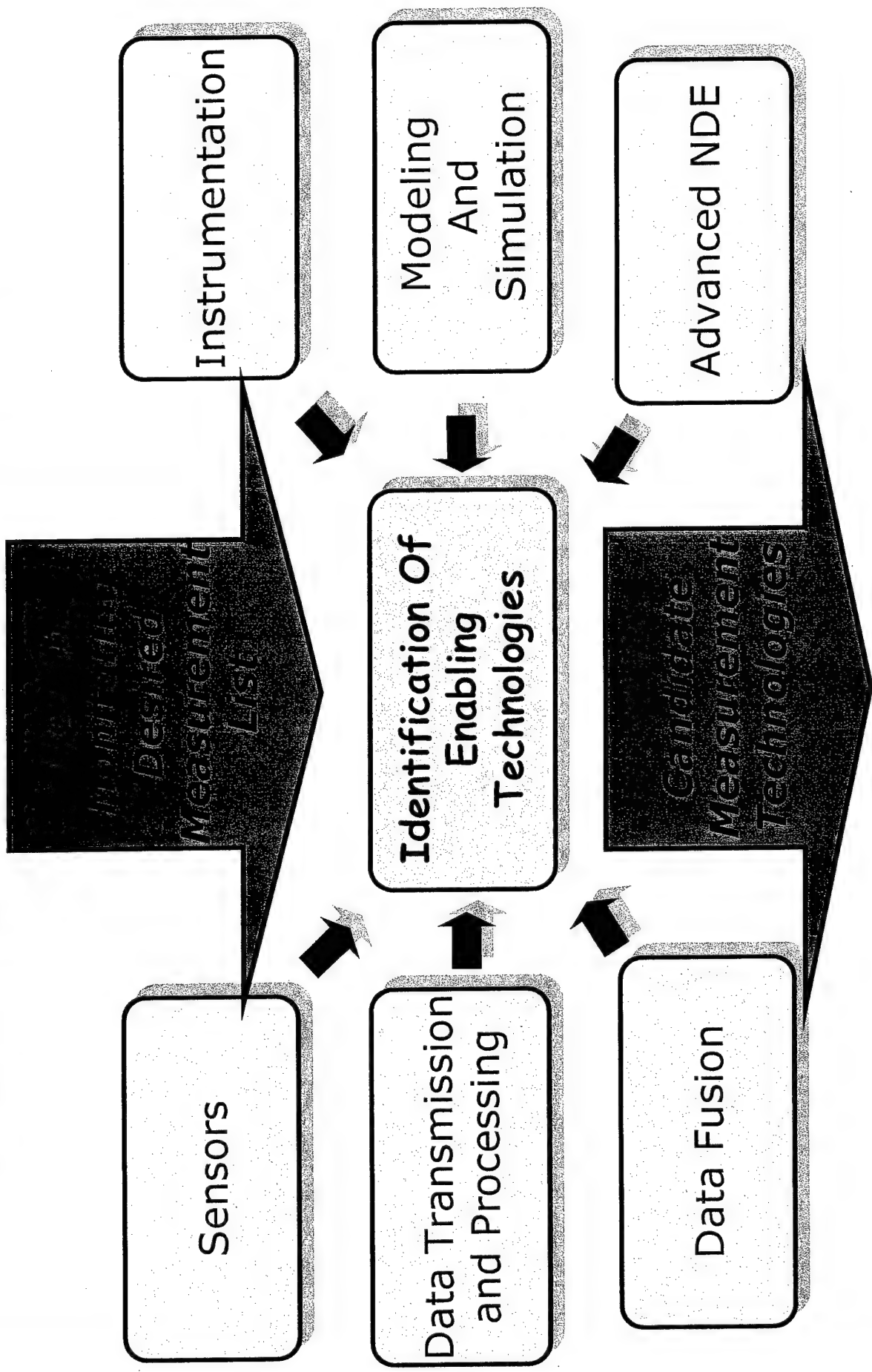
What is needed to transition technology to the  
identified SRM application?

What is required to demonstrate and validate  
the application of the technology?

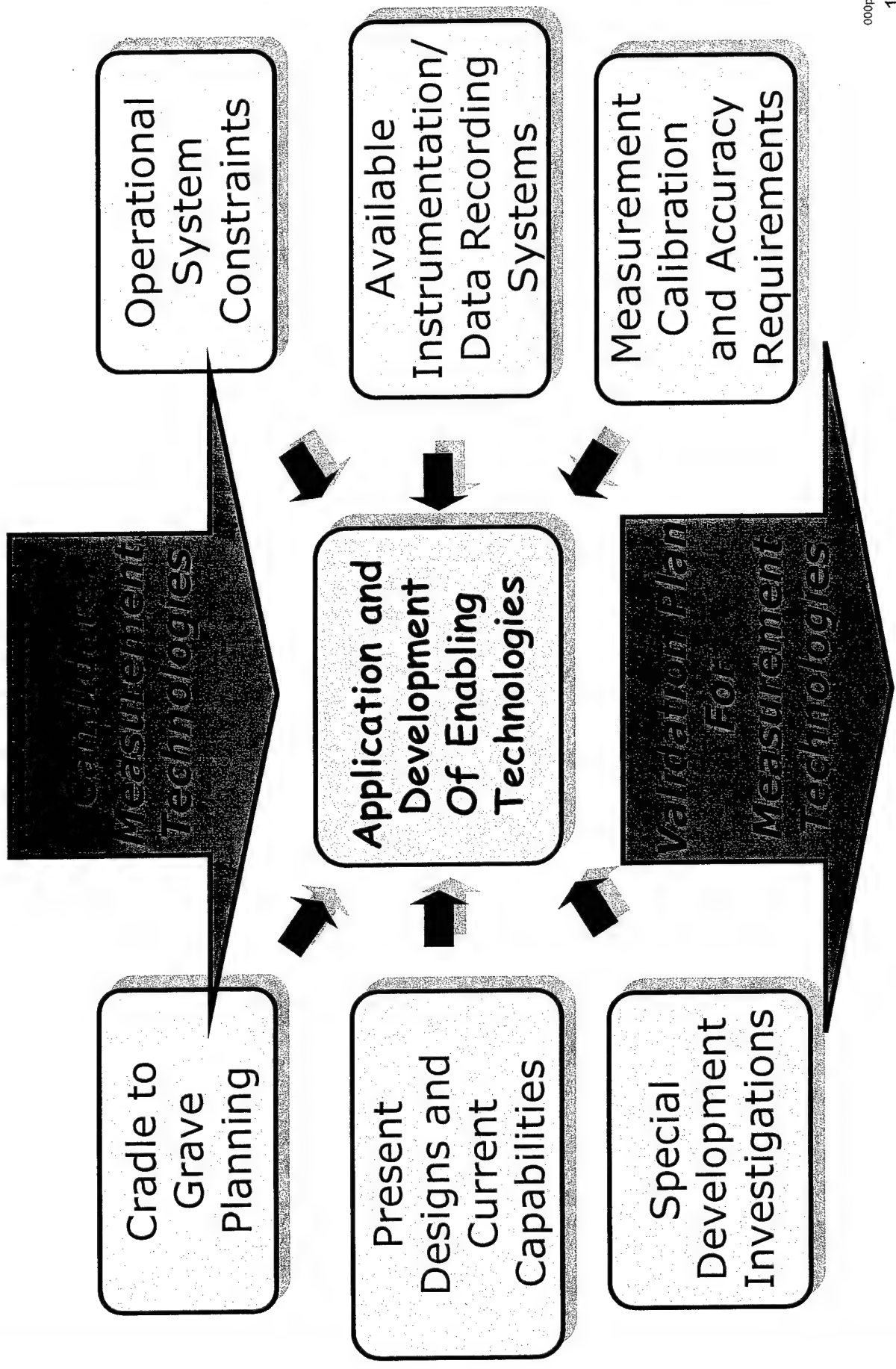
# Sensor Development Model Continued



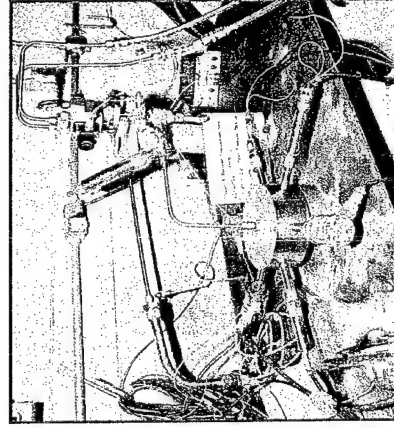
## Sensor Development Model Continued



# Sensor Development Model Continued

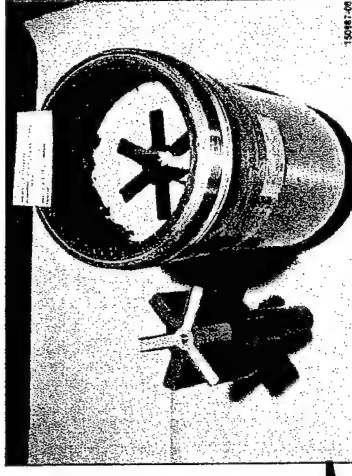


# Sensor Development Model Continued



Simulated  
Environments

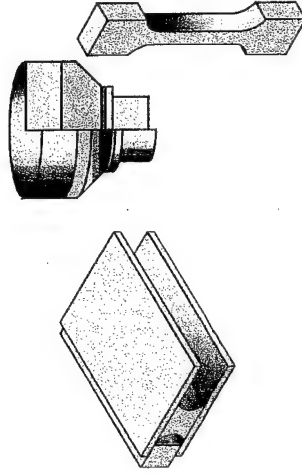
*Validation Plan  
For  
Measurement  
Technologies*



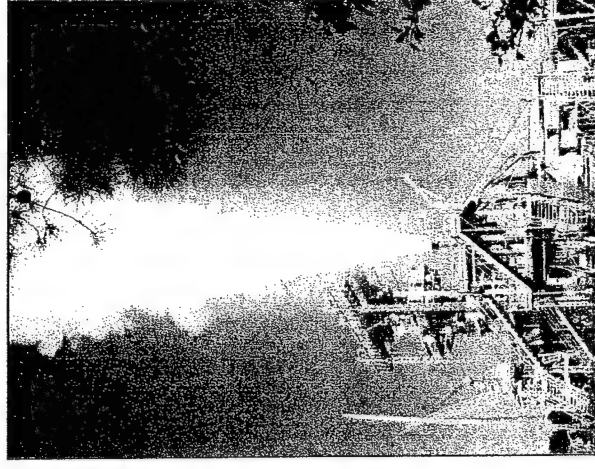
Analog Motor  
Testing

*Validation of Applied  
Technologies*

*Validated  
Measurement  
Technologies*



Lab Samples



Full-scale Testing

## Working Example

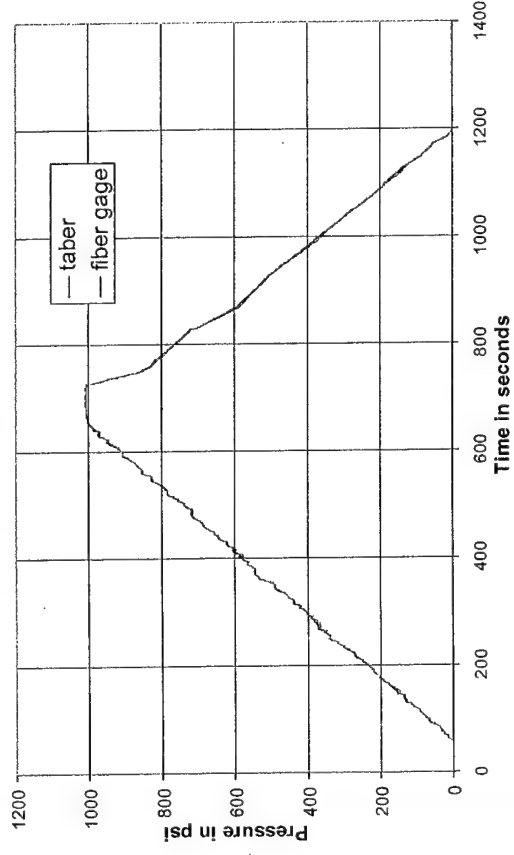
- Motor ignition data requirements identified
  - Pressure down the bore
  - Propellant stress and strain
- Fiber optics identified as possible enabling technology
- Application plan developed
  - Accuracy
  - Egress
  - Survivability
  - Signal conditioning
  - Etc.



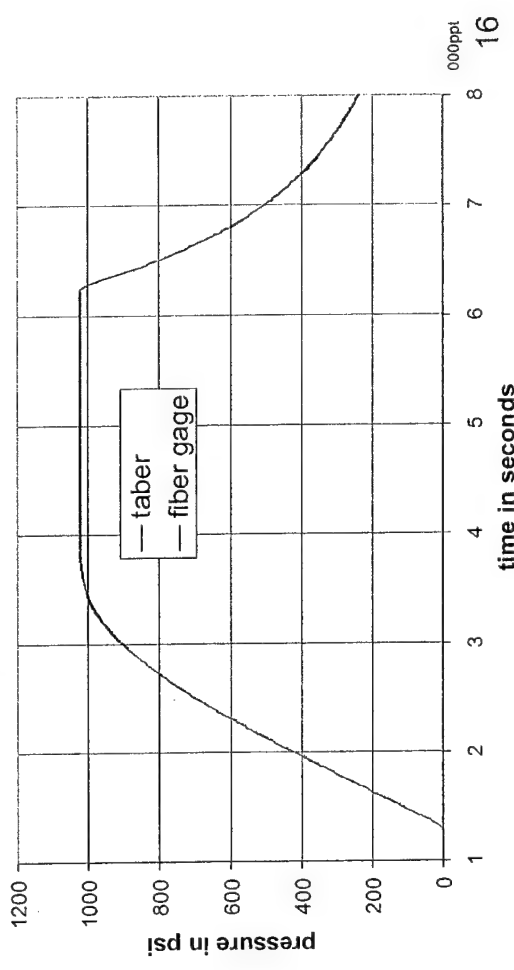
## Working Example Continued

- Fiber optic based sensors evaluated
  - Measurement of strain, temperature, bond-line stress and pressure
    - Fabry-Perot => pressure, strain (<10%), temperature
    - Fiber Bragg grating => low strain (< 2%), temperature, multiplexed sensors (potential for multi-axis development)
    - Compliant "stretchy" polymeric fiber sensor has potential for high strain ( $\approx 100\%$ ), needs development

Fiber Optic Pressure Gage Validation



Fiber Optic Pressure Gage Validation



## Working Example Continued

- Use of fiber optic technology for health monitoring of SRM's is promising

### Advantages

Intrinsically safe  
Immune to EMI  
Absolute measurements

### Technical Issues

Methods of attachment  
Methods of egress  
Survivability

- Fiber Optic gages are planned for use on a full-scale static test motor this year

## Working Example Continued

- Experience is allowing fiber optic manufacturer to understanding SRM industry needs
- Manufacturer took initiative to developed special gages for SRM applications
  - Pressure and normal stress sensors that measure perpendicular to fiber axis
  - Mini-extensometer
- Testing of new gages has started

## Summary and Conclusion

- Red-light green-light health monitoring of SRM's is the goal for the future
- Health monitoring of SRM's requires
  - Definition of concept from cradle to grave
  - Continued development of modeling and simulation tools
  - Development of sensors and sensor related technology
- Sensor developers are eager to understand and meet the needs of the SRM industry

# **A SOLID ROCKET MOTOR MANUFACTURER'S VIEW OF SENSORS AND AGING SURVEILLANCE**

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## ABSTRACT

The solid rocket motor (SRM) industry currently relies on destructive testing for determining long-term aging behavior. Cost associated with destructive testing has caused some programs to decrease or, in some cases, eliminate aging surveillance activities entirely. These reductions can, and have, resulted in increased risk of unpredicted failure. The development and use of sensors, capable of reducing or eliminating the need for destructive testing, is of prime interest to the SRM community. Historical attempts at using sensors for monitoring critical parameters, as materials age, have proven to be very difficult. Commercial sensor development companies have made some very impressive progress in recent years, but have little or no knowledge of the SRM industry requirements. Communication between SRM manufacturers and commercial sensor development companies is necessary to potentially reduce destructive testing. This paper addresses issues concerning implementation of sensors into SRMs, introduces a model for sensor evaluation and presents preliminary sensor test results.

## INTRODUCTION

Current service life prediction methodology relies on destructive testing of representative materials. Representative materials are often materials taken from operational assets. These materials are expensive to obtain and expensive to prepare and test in the laboratory. Once the test data are available to the engineer, it requires careful scrutiny to interpret the data. When all is said and done, an operational asset has been destroyed and the data obtained represents aging specific to that operational asset, at that specific point of age life. In order to understand aging trends and motor-to-motor variability, this process must be repeated on multiple assets.

Due to the expense and difficulty associated with interpreting the data collected over time, many programs do not pursue predictive aging. Some programs, in particular, small motor programs, adopt the philosophy of demonstrating reliability through functional tests. Static testing is a popular method of demonstrating reliability but does not predict when failures may begin occurring in an operational force. The probability of demonstrating a failure on this type of program is not high and once a failure is demonstrated the entire force is suspect.

Supporting a predictive aging program for SRMs has been, and continues to be, the nemesis of many program offices. New technology is continually being sought to help alleviate the current burden of surveillance testing. However, there are no new methods on the horizon that will allow radical changes to the data required for predictive aging. The current focus is to obtain data in a more cost effective way. New sensor technology is viewed as the key area of development that may be able to eliminate the need for destructive data, or as a minimum, provide a guide to reduce destructive testing.

Some requirements unique to implementation of sensors into SRMs are discussed herein. Companies that specialize in sensor development must understand unique requirements and goals of the SRM industry. SRM manufacturers are not capable of reaching those goals without heavy support from companies that specialize in sensor technology development. This paper presents some of the data requirements for a predictive aging

surveillance (AS) program, examines previous uses of sensors in the industry and suggests a model for sensor qualification and validation.

## BACKGROUND

AS approaches have evolved over the years depending on program need and industry capability.<sup>1</sup> The environments that govern major defense procurement decisions have been key drivers in this evolution. The large development and production budgets that propelled this industry to what it is today have become fading memories. What was built and tested to determine flaws and design weaknesses is now expected to be determined analytically. Programs are forced to minimize cost and maximize safety, reliability, and performance. It is essential for the SRM industry to utilize and develop sensor technology to meet the health management demands of the future.

There are two principle approaches for determining SRM reliability. First, is to demonstrate reliability through testing of operational assets. Second, is predicting reliability through analysis and test. Many programs implement a combination of these two approaches. Large motor programs have historically been most interested in predicting reliability because of the high cost of each asset. Small motor programs tend to rely on demonstrating reliability by static testing large numbers of motors. The use of sensors plays a larger part in the predictive approach. This paper addresses sensor requirements relative to a predictive AS approach.

Predictive data collected on AS programs are of two types, experimental and combined analytical and experimental. The experimental approach relies on trend analysis where testing is performed over time and data plotted as a function of age. These data are then compared to a specification limit or a failure limit, if available. The determination of failure limits in an experimental approach is difficult and is the main piece of data that separates qualitative and quantitative aging programs. Over-testing can be used to obtain failure limits. However, over-tests are designed specifically and do not relate well to the general motor population.

Programs that follow a combined analytical and experimental AS approach use analysis to relate the induced loads to failure limits. Accurate analysis allows the failure limits to be relevant to the entire force of motors. Material property data are collected over time and trend analyses are performed. These trends are used

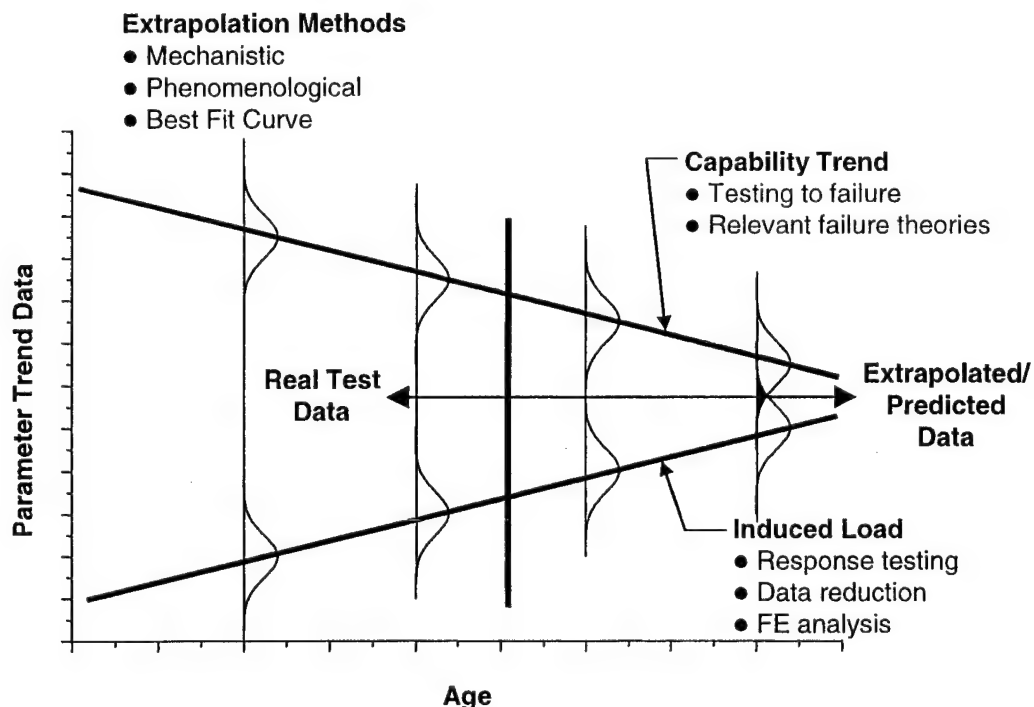


Figure 1. Schematic of Predictive Aging Surveillance Approach

to predict when failure might occur. Figure 1 illustrates the combined analytical and experimental approach. The top trend line represents the material failure limit or capability as determined in the laboratory. The bottom trend line represents the loads induced onto the material as predicted through analysis. There is a slope to the induced load trend curve that may not be intuitive. An example of an induced load that can vary with time is bondline stress. Typically, if the propellant stiffens with age, the induced bondline stress increases with age. This must be taken into account when addressing bondline failure modes. The probability of failure increases as the tails of the statistical distributions about the upper and lower data lines come closer together. Following the experimental approach, the top line in this figure would be a flat specification limit.

Figure 1 also illustrates another key point. The trend data must be extrapolated somehow for the approach to be predictive. There are three ways to extrapolate data. First is to place a best-fit curve through the existing data. This approach is not physics based and it results in low confidence in the extrapolation. Nevertheless, curve fitting is widely used in the industry because it is simple. Second is phenomenological extrapolation. This method entails accelerating the aging process by inducing false environments. Methods that are used to advance aging include elevated temperature storage, temperature cycling, vibration, etc.<sup>2</sup> The third method is sometimes termed mechanistic since it identifies the aging mechanisms and predicts future aging based on an assumed environment. This method requires understanding of the major aging mechanisms on a micro-level and a way of relating aging mechanisms to material property data. All three methods are currently used in the industry to gain confidence in extrapolated data.

## DATA REQUIREMENTS

Development of sensors requires an understanding of what needs to be sensed. The basic philosophy of aging programs has been provided. The actual data required to predict aging, following a combined analytical and experimental approach, fall into three basic types: 1) induced loads, 2) mechanical properties, and 3) chemical properties. Sensors that can be used for AS need to be able to measure these properties directly or, as a minimum, obtain secondary measurements that relate to the parameter of interest. This section defines some of the specific data required to predict service life.

Induced loads refer to loading during storage, transportation and handling, and motor operation. Primary storage loads include gravity, temperature, and humidity. Primary handling loads include temperature, humidity, shock, and accelerations. Primary operational loads include, pressure, gravity, acceleration, and vibration. The main use of sensors in the SRM industry have been in the area of understanding these induced loads. Sensors for obtaining this data currently exist but few SRM operational programs obtain this data routinely during storage and handling. This is probably because of the lack of credible models to interpret the data. However, models are improving and these data will be required for health monitoring.

Mechanical property data required for service life prediction can be divided into two categories: 1) material response data and 2) material failure data. Material response data include relaxation modulus ( $E_{rel}$ ), Poisson ratio ( $\nu$ ), and coefficient of thermal expansion ( $\alpha$ ). These parameters are used in finite element analysis programs to predict the stress and strain induced into the material for each loading condition of interest. The challenge is to develop sensors to measure these properties. It is not intuitive to the author how sensors can provide the data required for all analysis conditions. One issue is with the nonlinear viscoelastic behavior exhibited by solid propellant. The propellant properties vary greatly depending on the temperature of the material and the rate at which load is applied. This material complexity is what has driven the requirement for destructive testing. Material is extracted from a motor and tested under a wide variety of conditions of temperature, load rate, and pressure. Master curves are assembled for ease of use. The concept of obtaining equivalent data through direct measurement using sensors is beyond the author's comprehension. However, there is an alternative to obtaining this data that will be presented under chemical property testing.

The second type of mechanical property data relates to material failure or strength. Obtaining this type of data in situ is even more challenging than response data since it is inherently destructive. Failure or strength data are also dependent on temperature, load rate, and pressure. Currently material failure is required to obtain

this data. Again, there may be an alternative to obtain this data through the chemical properties as will be discussed.

The message here is that it does not seem practical or even possible to use in situ sensors to obtain material properties data for all analysis conditions. However, these data are still very important to obtain for model validation purposes. Current predictive tools can be validated or calibrated based on in situ material property data. Therefore, sensors capable of providing this data are still very important.

The third type of data required is chemical properties. Mechanical property changes are generally a result of subtle naturally occurring chemical changes or by mechanical damage. Sensors that can track the chemical changes responsible for the main aging mechanisms are of paramount importance to reducing or eliminating the need for destructive data. Microstructural models capable of relating the basic chemistry of an SRM system to material properties are just starting to emerge. This approach seems to have the most promise for meeting the future needs of aging programs. However, it is many years away from becoming a viable approach for any operational program. This entire methodology must be proven effective and eventually qualified for operational use.

The chemical properties of interest include migration or diffusion of different species through materials, especially near bondlines, and the rate of principle chemical reactions that relate to aging. For high-energy propellants, stabilizer depletion is a key parameter that has been linked to safe life. The most challenging aspects of this approach are defining the correct chemical aging mechanisms, developing sensors that can measure the needed parameters, and then relating the chemical properties to meaningful mechanical properties needed for predicting service life.

#### PAST SENSOR USE

Several SRM programs have attempted to develop/use sensors for obtaining valuable data.<sup>3,4</sup> However, all of these programs are either research or special studies. The only sensors used on operational SRMs as a generality are pressure transducers, thermocouples, accelerometers, and environmental monitoring devices for recording temperature and humidity. These types of sensors provide an understanding of the induced loads. Use of sensors for determining chemical and mechanical properties have been limited. This section briefly describes some of these programs.

One ambitious large motor program used sensors to validate structural analysis tools. This program executed two full-scale demonstration tests with a good variety of instrumentation. One test focused on ignition. The other test focused on thermally induced loads.

The cold rapid pressurization test required special casting of a motor with 14 imbedded stress gages, seven normal and seven shear stress sensors.<sup>3</sup> In addition to the embedded gages, there were 64 other gages for measuring strain, displacement, pressure, and temperature. The purpose of the test was to validate the structural analysis model used to predict ignition conditions. A special diffuser was built to distribute the cold gas into the chamber to simulate the rapid loading conditions during motor ignition. Sixty-two of the 78 gages produced data for a 79 percent survival rate.

The thermal soak test required the special cast of a motor with 14 embedded stress gages, seven normal stress and seven shear stress. In addition to the embedded gages there were 56 other sensors that measured displacement, strain, and temperature. The measured data was to calibrate and validate the thermal analysis finite element model.

The United Kingdom (UK) has worked with Micron Instruments to develop improved normal stress gages and data recorders specifically for use in SRMs. These gages have been used to measure normal bondline stress during cure, storage, and ignition conditions. The leads for the gages can be taken out of the motor through a small hole drilled in the case. This provides an ambient pressure reference to the inside of the gage



and is isolated from pressure during ignition. The UK and Micron are currently making improvements to the gage and data recording device.

Another large motor program took a different approach to validating their structural analysis models. Instead of using full-scale motors this program built special subscale motors that could be tested under a wide variety of loading conditions. The advantage of using subscale motors was that multiple motors could be tested to better understand the statistical variation of the testing and material behavior. The disadvantage was that the data did not relate directly to the full-scale motor. Nonetheless, the structural models were validated. The sensors used on the subscale motors included normal and shear stress, displacement, Hall effect, and thermocouples.

Neither the large motor programs have attempted to include these types of gages into operational motors for long-term health monitoring. Both programs focused their efforts on specially designed assets for the purpose of validating analysis methodology.

The Service Life Prediction Technology (SLPT) program is a current program focused on determining the link between chemical and mechanical properties in three different material systems. The aging mechanisms of each system are being modeled. The changing chemical properties are being linked to mechanical properties through a microstructural constitutive theory. This type of approach provides a possibility of determining mechanical response and failure properties needed for all analysis conditions. The SLPT program is planned to operate through 2002. This program will define the material properties of interest for health monitoring of the three material systems that are in the program.

The Extended Service Life Prediction program was a research program with a subtask to evaluate sensors for SRM health monitoring. The program evaluated four different sensing techniques that were capable of being used in situ, related directly to aging parameters of interest, and are nondestructive. The sensor techniques included ultrasonics, infrared sensors, dielectric sensors and fiber optic sensors. The program goal was to relate the nondestructive (NDE) data to mechanical properties used for service life estimates.

The Propellant/Case Interface Technology program included a subtask to relate chemical and mechanical properties at the bondline. The chemical and mechanical property changes at the bondline are usually exaggerated as compared to bulk materials. These complex material behavior gradients were the subject of the program. Stress and strain gradients in the materials next to the bondline were related to chemical property gradients. This testing was done destructively but is a good source to help understand the link between chemical and mechanical properties.

Health monitoring of composite cases has become an industry issue since some recent failures have been associated with damaged cases. The Space and Missile Systems Center of the Air Force Materiel Command funded a program to demonstrate a health monitoring system for graphite-epoxy motor cases. This program relied on fiber optics to continuously monitor and record adverse impacts, accelerations, strains, or environments that may cause damage to composite cases.

There are undoubtedly other programs that have developed sensors for use in SRMs. However, to date there are no operational programs that use embedded sensors as a method of monitoring the health of their SRMs.

### SENSOR DEVELOPMENT

It is very enticing to imagine being able to obtain critical aging data from a sensor embedded in every motor in the force. The data would be directly from the motor rather than from test specimens that are assumed to relate to the motor. A time history for each motor would be obtained for accurate motor-to-motor variability assessment. Motors subjected to widely varying environments could be evaluated individually and not as a general population. Development of sensors that can provide this information is the key to success.

Realizing this goal requires capability that does not currently reside within the SRM community alone. Expertise in the areas of chemical, mechanical and physical sensor development, miniaturization, wireless data transfer, data fusion, modeling and simulation, networking, etc., is all required. Most companies who develop sensors and data transfer methodologies are not familiar with the unique environments or requirements of the SRM industry. Integration of these capabilities is required to successfully develop a health monitoring capability.

There are much larger industries than ours that have seemingly endless funding that are working to develop sensing technology for their own use. Industries such as biomedical, energy, telecommunications, aircraft, and public transportation have implemented sensor technology into many of their surveillance operations. The SRM industry can benefit from this work by teaming with companies that have already developed useful technology. Technology developed by other industries can be tailored to meet the extreme requirements of our industry.

Table 1 lists some of the unique and varied environments SRMs see during their life span. The sensors

**Table 1. Typical SRM Environments**

<b>Loading Type</b>	<b>Duration of Loading</b>	<b>Temperature During Loading</b>	<b>Pressure During Loading</b>	<b>Vibration and Acceleration</b>
Handling	Days	≈170° to -50°F	Ambient	Varied
Storage	30+ years	≈170° to -50°F	Ambient	Varied
Ignition	≈5 to 120 sec.	≈5,000°F	≈500 to 3,000 psi	Varied
Captive Carry	Cyclic	Ambient to altitude	Ambient to altitude	Varied

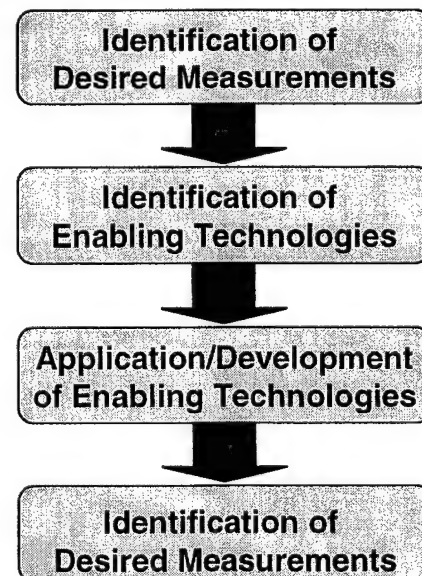
either have to be designed to survive these environments or be protected from them.

#### SENSOR DEVELOPMENT MODEL

The purpose of most models is to provide a mechanism for meeting a requirement. What is the requirement of health monitoring? The ultimate requirement, as stated by several SRM customers, is to have a red light that indicates the motor has aged out or a green light that indicates operational readiness. This is a very difficult task but one that will never occur without a focused, well-directed effort. This section addresses a model that will provide direction for health monitoring sensor development. It is a preliminary model that will be improved upon with use.

The model addresses four steps for health monitoring sensor development. These four steps are shown in Figure 2 as: 1) identification of desired measurements, 2) identification of enabling technology, 3) application of technology, and 4) technology validation. Some of the details of these steps are discussed below.

Maximizing the efficiency of health monitoring sensor development efforts requires guidance. The first step of the model is to identify data that can have the largest impact on an SRM program. Figure 3 shows areas that may be considered when attempting to identify the primary data requirements. These areas cover safety, reliability, risk, and cost issues that programs typically deal with during production and aging. This information needs to be prioritized into a list of

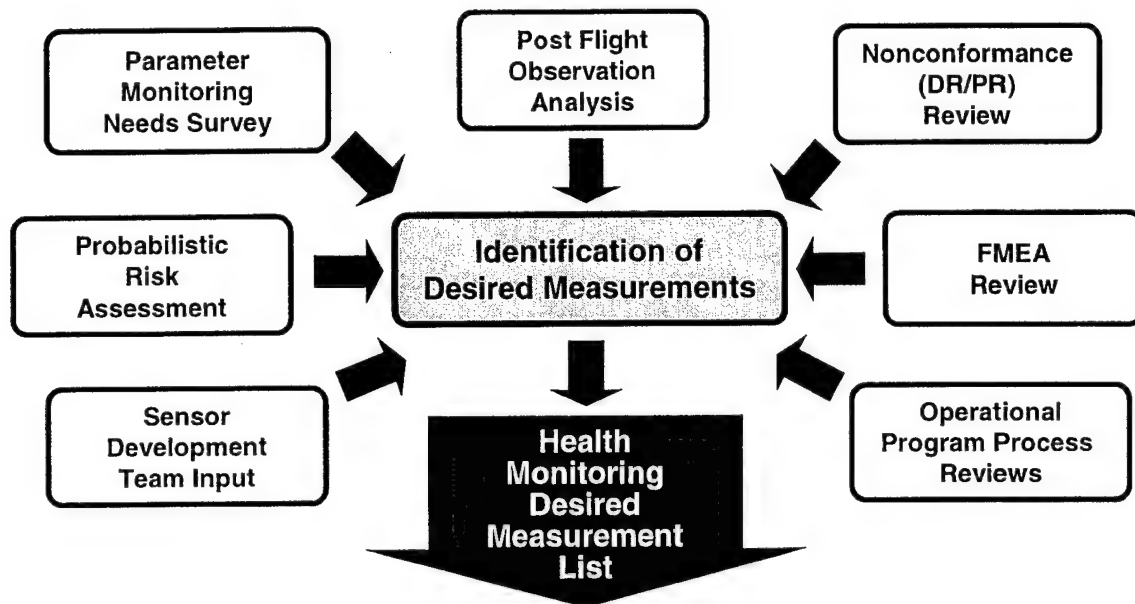


**Figure 2. Sensor Development Model**

desired measurements for health monitoring of each missile system.

Once the list of desired measurements has been prepared, technology required to obtain those measurements should be identified. Figure 4 identifies general technology areas to be considered. Technology relating to sensors and instrumentation include identifying existing or needed gages and identification of acceptable data recording and transmission schemes that meet all requirements. Data recording and transmission for health monitoring is an issue that requires operational program input. The end item users are the ones who will be responsible for obtaining the data from recording devices. Frequency of data transmission, methods of transmission, and battery life are issues that need to be addressed.

The data obtained from sensors, and definition of how the data is to be used, would ideally be defined



**Figure 3. Model for Identifying Desired Measurements**

during motor design efforts. This would allow for development of a database that covers the entire life of the motor from production through aging and operation. The data obtained may be quantitative or qualitative in nature. Qualitative data are not used for predictive aging but may be used to guide and potentially reduce the need for dissection and destructive testing. Quantitative data would ultimately be integrated into modeling and simulation routines to determine the effects of aging on predicted motor performance.

Figure 4 also shows technology for advanced NDE methods. These technologies have historically been used to detect flaws. Flaw detection would become a form of validation of sensor health monitoring. There are currently programs that are attempting to obtain quantitative data from NDE methods. It would be ideal if these techniques could provide information that fit directly into a predictive AS approach.

After candidate technologies have been identified for meeting requirements of desired measurements, it becomes critical to work out possible application issues. Application issues can differ between the SRM manufacturer and the end-item users. Integration of requirements must be considered. This is not a simple process but becomes absolutely essential for long-term health monitoring.

For example, if sensors are to be embedded in every SRM during fabrication, the manufacturer must define: 1) when this is accomplished in the manufacturing flow, 2) impact to the program in terms of cost and schedule, 3) how it may affect continued handling through manufacturing, etc. For the end-item user there are

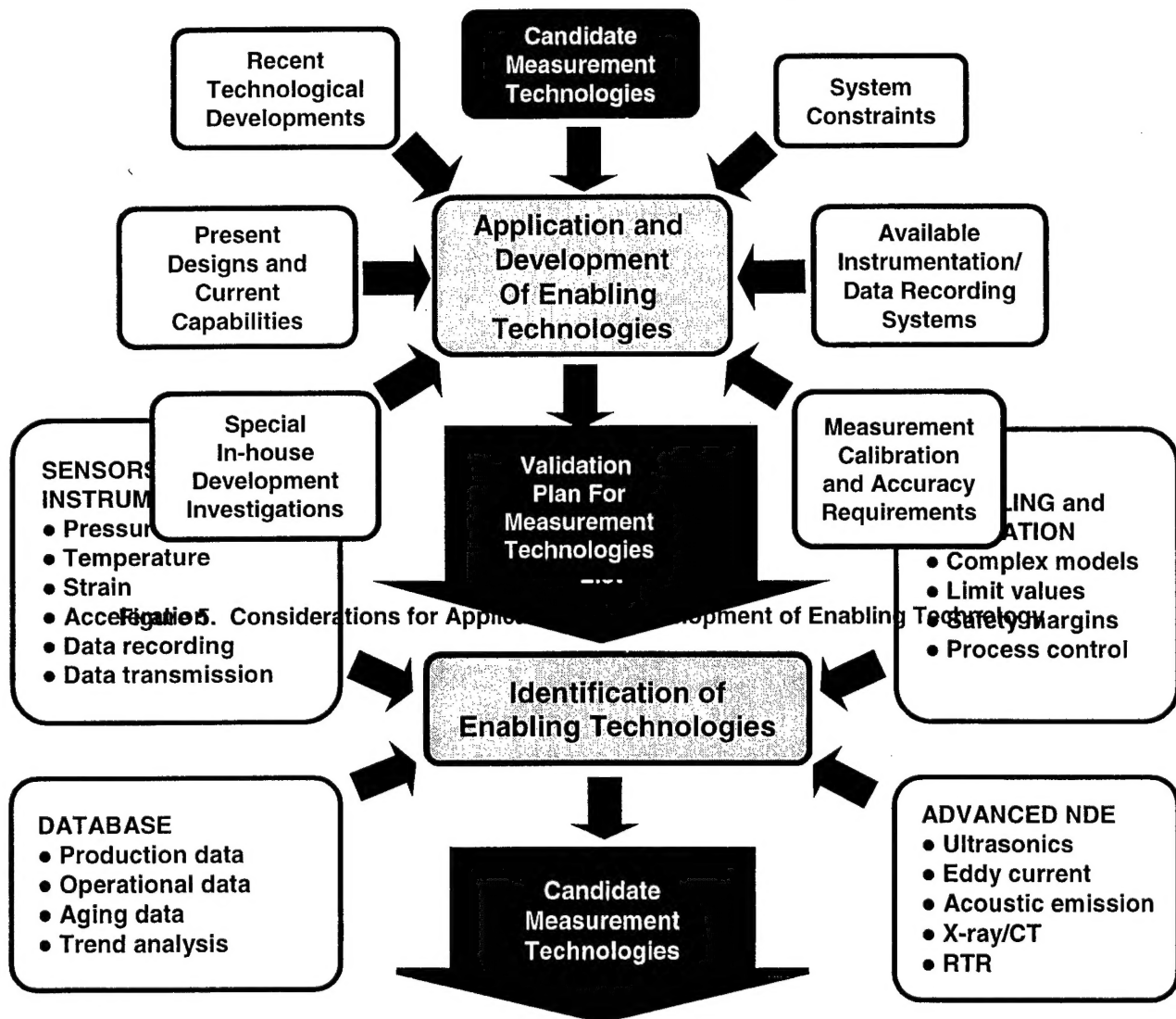
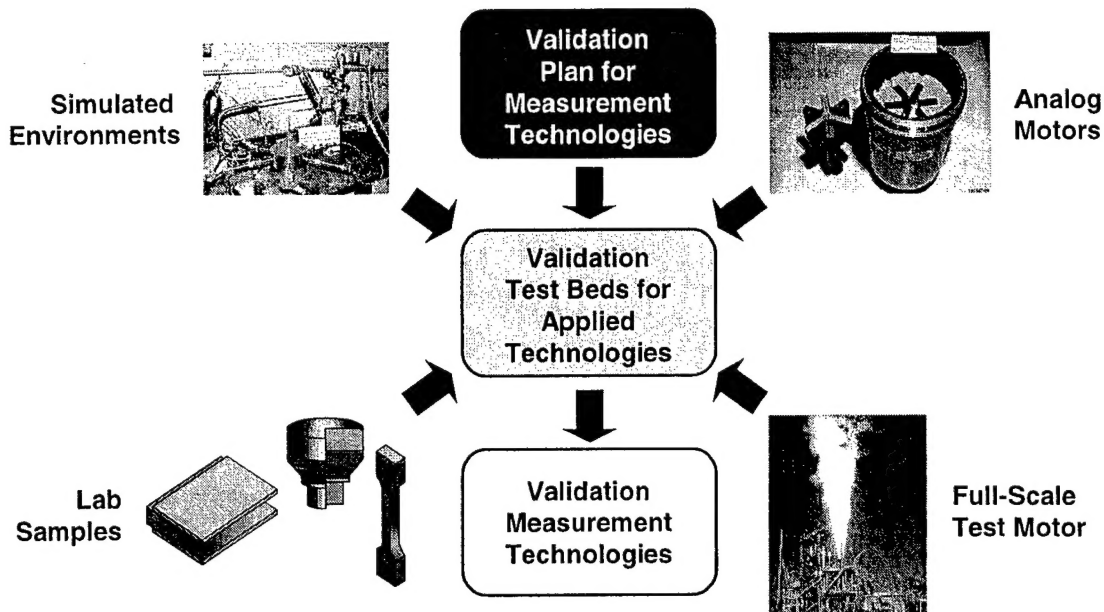


Figure 4. Model for Identifying Enabling Technology

issues such as: 1) interface compliance documents (ICD), 2) instrumentation requirements for obtaining and interpreting data, and 3) training, etc. Figure 5 illustrates some of the considerations to be taken into account.

In the case where there is not a good match between existing technology and application requirements, special development programs may be needed to create the desired capability. These programs would have well-defined objectives based on the definition of requirements that comes out of the development model.

Technologies that make it past the first three steps of the development model shown in Figure 3 will be subjected to validation testing and possible qualification. Figure 6 shows the different levels of validation options. Validation typically starts with simple laboratory samples tested in very controlled environments.



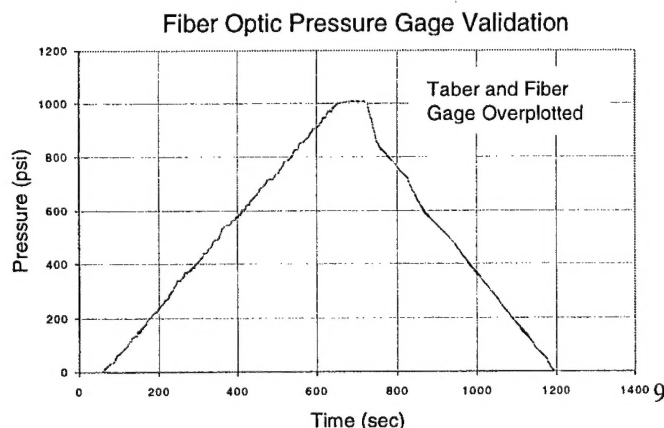
**Figure 6. Options for Validation Testing**

Sensors that meet requirements at this level may then be introduced to analog motors that can simulate actual motors more closely. The ultimate test of any sensor is in the intended application. Since SRMs are costly to produce, validation efforts are usually done in steps.

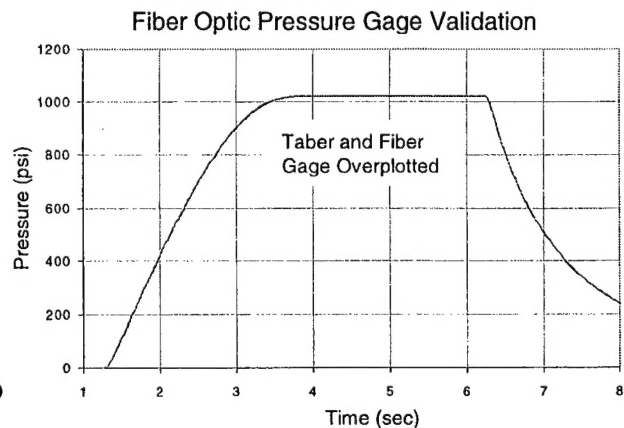
### PRELIMINARY SENSOR DATA

Fiber optics is an enabling technology that offers definite advantages for embedding sensors into SRMs to measure stress, strain, pressure, and chemical properties. They are inherently safe since light is the only source of energy needed for the gages to function. The gages are very small and do not drift with time or require the same kind of calibration as electromechanical-type sensors. Fiber optic technology is ideal for testing out the sensor development model.

Preliminary test data have been obtained from fiber optic gages used to measure pressure inside of a pressure analog motor. The gage was fed into the cavity of an analog motor through a specially designed feed-through. Pressure of 1,000 psi was applied to the inside of the motor at two different rates, one semi-fast and one slow. The motor also had a standard Taber pressure gage installed for validation purposes. Figures 7 and 8 show identical comparison results of the fiber optic and Tabor pressure gages. These preliminary results are



**Figure 7 Low-Rate Pressure Test**



**Figure 8 High-Rate Pressure Test**

very promising.

There are, however, several issues with fiber optics that need to be addressed and overcome before this technology can be used in general in SRMs. Fibers are typically made from brittle material such as glass. This results in being fragile and difficult to handle. However, fiber optics has been successfully applied to instrument bridges and deep-sea oil drilling operations that are very severe environments. Current data acquisition rates may not provide enough data to capture some ignition events of interest. The range of strain measurement may not be adequate for use with propellant. Whether fiber optics can be designed to withstand motor operational environments is still unknown. At this point in time there are many more questions than answers.

Thiokol has worked with several fiber optic-manufacturing companies who have off-the-shelf optic gages. Improvements to off-the-shelf technology have been made by the manufactures to meet some special requirements of the SRM industry. Some of these improvements include development of a bondline normal stress sensor and a normal pressure sensor that are perpendicular to the fiber axis and a mini-extensometer. Testing of these gages has not yet started. Development of methods for measuring strains typical of SRM propellant seems possible but requires additional effort.

### SUMMARY AND CONCLUSIONS

The message from our customers is clear – eliminate the need for costly destructive testing for service life evaluation. Development of sensor technology capable of providing the required information is the only foreseeable approach to accomplish this challenge.

There are no radical new ways of predicting service life on the horizon. Predicting the potential for motor failure requires chemical and mechanical property information as a function of age. Sensors need to be developed that can provide the necessary information to fit predictive models. The best approach to obtain material response and failure properties nondestructively for all analysis conditions is through the continued development of microstructural theories capable of linking the chemistry to these properties.

Development of new sensors, data recording, and transmission methods requires expertise that does not currently reside in the SRM community. Companies that have been developing these capabilities in other industries and have significant knowledge and experience are needed to meet the challenge.

The sensor development model provides a sound approach and is intended to help focus effort toward the most meaningful applications. The model can be used to match existing technology with needs as well as identify technology areas that need further development.

The single most important factor that will propel this endeavor to successful completion is the end-item users. SRM health monitoring must begin at the design phase. Fabrication specifications and requirements generally do not adequately address health-monitoring requirements if they are addressed at all. Requiring manufacturers to address these issues is essential for successful SRM health monitoring.

### REFERENCES

1. "Service Life Assessment History," JANNAF S&MBS Service Life Workshop, Hill AFB, Utah, 22-26 March 1998.
2. L. H. Layton, "Chemical Structural Aging Effects," Final Report, AFRPL-TR-74-77, October 1974.
3. "Graphite-Epoxy Motor Casing Health Monitoring Systems Demonstration," SMC-TR-99-28, 1 June 1999, prepared by The Aerospace Corporation for Space and Missile Systems Center.

4. Buswell, J.; Chelner, H.; Hubinger, M. and Spinks, G., "Characterization and Use of Bond Stress Sensors in Tactical Rocket Motor," AIAA 2000-3139, 36<sup>th</sup> AIAA/ASME/SAE/ASEE Joint Propulsion Conference and Exhibit, 16-19 July 2000, Huntsville, Alabama.